

Aeolian Induced Erosion and Particle Entrainment  
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## **Abstract**

The Granular Physics Department at The Kennedy Space Center is addressing the problem of erosion on the lunar surface. The early stages of research required an instrument that would produce erosion at a specific rate with a specific sample variation. This paper focuses on the development and experimental procedures to measure and record erosion rates. This was done with the construction of an open air wind tunnel, and examining the relationship between airflow and particle motion.

## **Introduction**

As more and more operations are planned for on the moon several real problems will arise. Two of these problems will be the erosion of the lunar soil due to repeated landings and the entrainment of lunar soil in rocket exhaust. Repeated landings will not only cause drastic erosion, but the entrained particles create a serious hazard to surrounding equipment. It is estimated that rocket exhaust propels lunar regolith to mach six. Future engines will most likely exceed this value. In order to address these problems steps had to be done.

First and foremost this problem has never been fully addressed. Not only have there been very few tests done with lunar stimulant but almost no tests have been done with actual lunar regolith. Also a large step that must be overcome is understanding the inter-particle interaction of the individual particles. Lunar regolith is unlike any substance on Earth. The vacuum conditions create a non-Stokesian ballistic flow regime. This means that the analytical models have to be developed and the traditional governing physics equations about flow and granular material cannot directly apply. Because of the lack of atmosphere on the moon the regolith particles have a highly angular shape.

These sharp edges on the particles make the particles hook onto each other and unhook from each other. This creates a very unusual particle interaction. In some circumstances the soil will behave like a liquid and in others it will behave like a granular material with characteristics of a material with a much higher size distribution.

## **Problem**

The first steps for determining the erosion rate and the quantity of entrained particles in the air is to develop a method to erode and entrain the particles. Since no instrument was available for this an open return wind tunnel was designed and built.

## **Method of Solution**

Certain requirements had to be met due to the nature of wind tunnels intended use. Pictures are provided in the appendix. A square test section was used so that instrumentation would not be distorted by a curved surface. (Figure 1) An open return design was needed so that particles would not be re-circulated through the test area. The entire assembly had to be mobile since the particles would be exhausted into open air, thus it was constructed and mounted on carts for this desired mobility. (Figure 2) In order to keep the system mobile a high powered tube-axial fan could not be used so a standard industrial fan was used with simple modifications. (Figure 3) And the drive section needed to be located behind the test area so that a vortex was not created in the test area. Conversely plans are available to install a centrifugal fan to the front that can be used individually or in conjunction with the rear fan. A sample box had to have easy installation and removal from underneath of the test area and it had to be flush with the bottom inside surface of the test area. (Figure 4) Having different detachable sample boxes was needed so that different samples could be prepared in different ways. The boxes were designed to have a two inch gap on either side so that boundary layer flow for the vertical walls would not interfere with the specimen. A five inch space was provided

in the front and back of the sample box to allow for catch screens and settling chambers. A settling was not intended to be used since the desired flow was to be turbulent. (However an area was provided for a settling chamber in the designs if one was to be desired in the future. The length of the test area also allows for “settling length”. This is an area just behind the settling chamber that allows the flow to settle after leaving the settling chamber and before it enters the test area.) In order to reduce energy loss due to surface friction, galvanized metal sheets were used for the compressor and diffuser. A lid on the top of the test area allowed for accessibility to the test area from above. The test area, sample boxes, and lid were made from 1/4 in. lexan. An XY treaded pegboard was installed directly underneath the test area so the instrumentation could be mounted securely for accurate data collection.

The dimensions of the wind tunnel are:

- Overall Length: 2.7m (9ft)
- Overall Height: 1.8m (6ft)
- Fan Diameter: .863m (34in)
- Fan speed: 1100 RPM
- Test Area: .0929m<sup>2</sup> (1ft<sup>2</sup>)
- Fan Output: 1.24m<sup>3</sup>/s (44ft<sup>3</sup>/s)
- Compressor:
  - Opening: .9144m x .9144m (3ft x 3ft)
  - Length: .4572m (18in)
  - Exhaust: .3048m x .3048m (1ft x 1ft)
- Diffuser:
  - Opening: .3048m x .3048m (1ft x 1ft)
  - Length: 1.016m (40in)
  - Exhaust: .9144m x .9177m (3ft x 3ft)
- Sample Box:
  - Area: .546m x .190m (21.5in x 7.5in)
  - Volume: 1) 4600cm<sup>3</sup> (282.18in<sup>3</sup>)
  - 2) 1320cm<sup>3</sup> (80.625in<sup>3</sup>)

The peak maximum velocity in test area is 13.96 m/s (31.24 mph). The average maximum velocity is 13.71 m/s (30.68 mph). These velocities were determined by using a digital manometer along with the provided slide ruler to compensate for relative humidity, barometric pressure, and air density. As the flow travels down the test area the velocity at the exhaust drops to approximately 13.46 m/s (30.11 mph).

The construction and calibration of the wind tunnel has taken the majority of the time. While tests have been conducted and videos filmed for calibration no detailed experiments have been done. These calibration tests were done to verify that the speeds achieved in the test area generated the needed shear stress to erode particles. The speeds reached inside the test area easily erode ASTM 20-30 construction sand. This material has a size of .600mm and is 97% retained on the # 30 sieve.

In order to predict and determine erosion rates the cause of the erosion needs to be addressed. Many theories exist about wind erosion. One theory presented by Leonard Roberts in his paper “The Interaction of a Rocket Exhaust with Lunar Surface” about the

relation of the effective shear stress of the soil with the shear stress generated by the exhaust is leading the research in this area. Another theory focuses on the lifting forces and affects on the particles.

There are two main approaches on this theory. One addresses the change in velocity due to the boundary layer. This proposal states that due to the difference in velocity from the top and bottom a differential pressure is created causing the particle to lift and become entrained in the air stream. Non-supporters of this idea say that for very fine particles there is not enough of a velocity difference to generate differential pressure.

The other approach considers the rolling effect of the particle before it lifts off the surface. In order for a particle to achieve enough lift to become airborne it must first overcome the forces of gravity and inter-particle cohesion on it. Drag and lift from the air or gas will pull the particle away from the surface. Once entrained the forces of drag induced on the particle must be overcome in order for the particle to remain entrained. At high Reynolds numbers the coefficient of drag becomes constant for angular bodies. For spheres in laminar flow the drag force comes from Stokes law, which is:

$$F_D = 3\pi\mu V_o d$$

In completely turbulent flow the drag is a function of the velocity to the second power. So, when solving the coefficient of drag for two-dimensional bodies;

$$C_D = \frac{F_D}{A_p \rho V_o^2 / 2}$$

simultaneously with the first equation yields:

$$C_D = \frac{24}{Re}$$

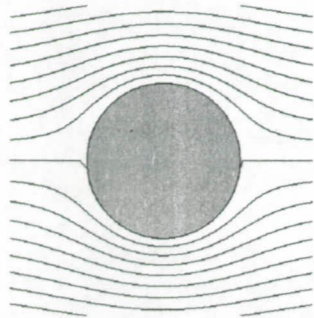
There are several correlations for the drag coefficient of a sphere. The one used here is:

$$C_D = \frac{24}{Re} (1 + 0.15 Re^{0.687}) + \frac{0.42}{1 + 4.25 \cdot 10^4 Re^{-1.16}}$$

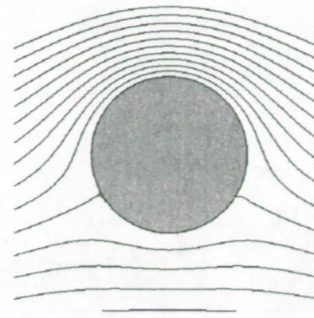
This came from Clift and Gauvin's book titled "The Motion of Particles in Turbulent Gas Streams". This is for Reynolds numbers up to  $3 \times 10^5$ . As Reynolds approaches zero this reduces to the Stokes equation.

Before a particle becomes fully air borne it begins to roll. This circulation means that the velocity of the gas next to the surface of the particle is equal to the velocity of the particle surface. This can be easily visualized by placing a cylinder in a fluid and spinning the cylinder along its axis. As the speed of rolling increases saltation occurs. A diagram of saltation is provided in the appendix. (Figure 5) The effects of saltation only need to raise the particle enough to allow flow to get underneath the particle. Now flow velocity is on both top and bottom of the particle. If you combine the circulation velocity of the rotating particle with the flow velocity on the top and bottom it can be seen that the

velocity is increased on the top and decreased on the bottom. Below are two figures that show the flow around the particle with no rotation and the other figure shows the combination of rotation and flow around the particle. The rotation is clockwise and the flow is from left to right.



Free stream with no rotation



Free stream and rotation combined

With higher velocity across the top and lower velocity across the bottom a pressure differential is created between the top and bottom. Note the two stagnation points in the figure with the combined free stream flow and rotation. This is consistent with the Bernoulli principle. This pressure difference created from rotation and translation of the particle is called the Magnus effect. This is the same concept that makes a curve ball curve when thrown by a pitcher. The lift coefficient is defined as:

$$C_L = \frac{F_L}{A_p \rho V_o^2 / 2}$$

$A_p$  is the projected area.

So when the lifting force exceeds the gravitational and cohesive forces the particle begins to rise. Once entrained the lifting forces must equal or overcome the drag forces to keep the particle aloft.

The erosion measurements have to be taken with respect to time. The mass of the eroded particles over time will provide us with an erosion rate that can be scaled to lunar situations. Since erosion does not only pertain to the mass of particles, but also the number of particles the optical density of entrained particles will be used to determine the number of particles. The optical density experiments will also help in the development of obstruction sensors that are to be used on landing craft to avoid hazards that cannot be seen due to the exhaust and particles being blown away.

Until more exact equations can be formulated a good first step for predicting erosion can be to use the wind shear velocity,  $u^*$ , for initial movement of the different grain sizes based on the Bagnold equation:



$$u^*_t = A \left( \frac{\sigma - \rho}{\rho} g d \right)^{0.5} \quad (1)$$

where:

$\sigma$  = particle density

$\rho$  = air density

$g$  = acceleration due to gravity

$d$  = mean particle diameter

$A$  = coefficient of turbulence approximately equal to 0.1 for particle friction Reynolds number  $> 3.5$ .

In the past this equation has proved to be fairly reliable and is considered a benchmark formula. The threshold wind speed at a specific height to the surface can be determined by substituting the result from Equation (1) as  $u^*$  in the widely used form of the Prandtl equation:

$$U = 5.75 u^* \log \frac{z}{z_0} \quad (2)$$

where:

$u^*$  = (threshold) shear velocity,  $u^*_t$

$z_0$  = surface roughness

$z$  = height above surface

$U$  = wind speed at height  $z$

The result from Equation (2) indicates the required wind speed at the specified height for erosion of sediment on the surface to begin. Using this it can be determined which area of the lunar surface can withstand the highest exhaust velocity and in turn have the least amount of erosion.

### Discussion and Conclusion

The construction and design of this wind tunnel will prove to be a practical and effective way of testing actual erosion and greatly improve the understanding of how lunar soil interacts during erosion. All of the requirements for the wind tunnel were met however the construction time took longer than anticipated which did not provide much time to complete experimental work. It is at this time that the experiments are beginning to be conducted. With the knowledge gained thus far regarding erosion and particle entrainment the experimental process will move quickly. The adjustability of the wind tunnel should make it usefulness to future experiments.

### **Acknowledgements**

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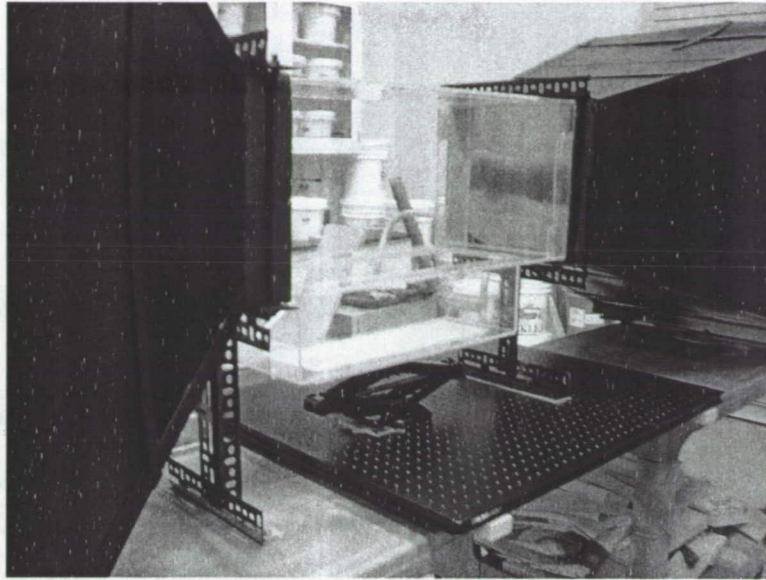


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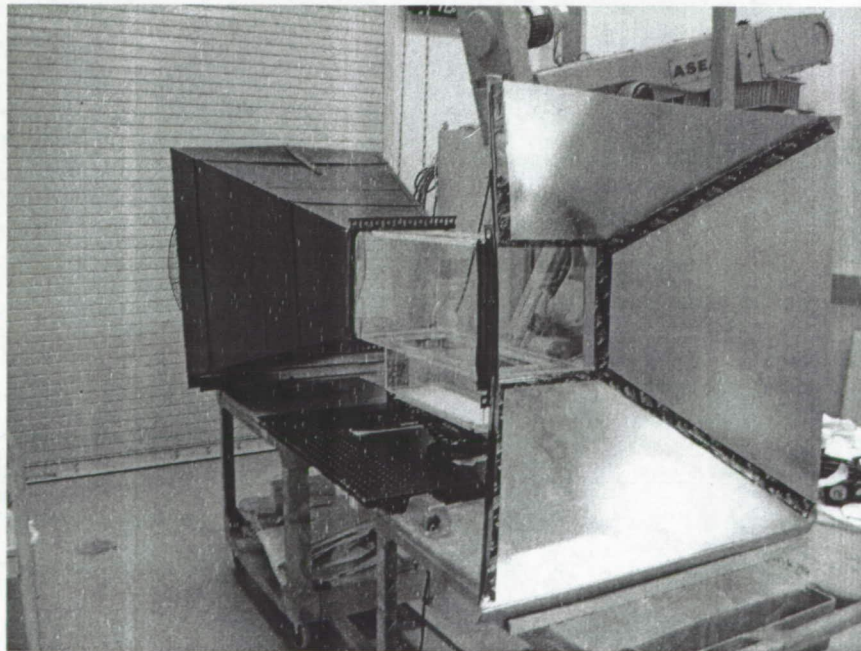
## Appendix

Figure 1



Test area looking along the compressor toward the diffuser with large sample box.

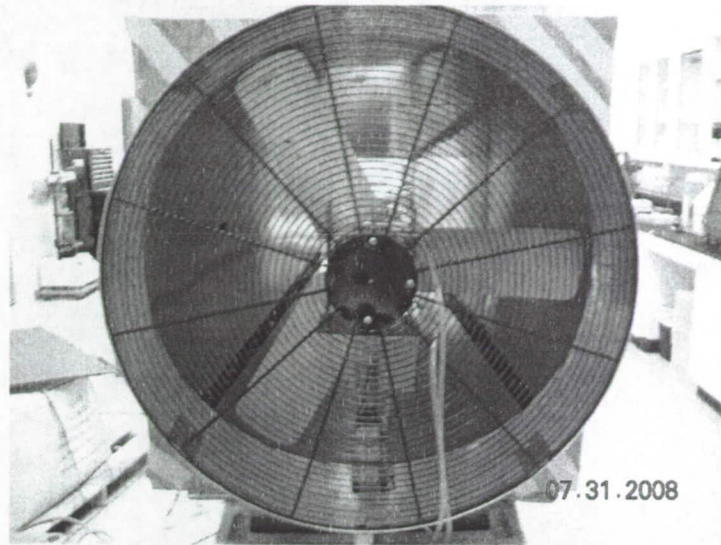
Figure 2



Open air design to prevent re-circulating particles; mounted on 2 utility carts.

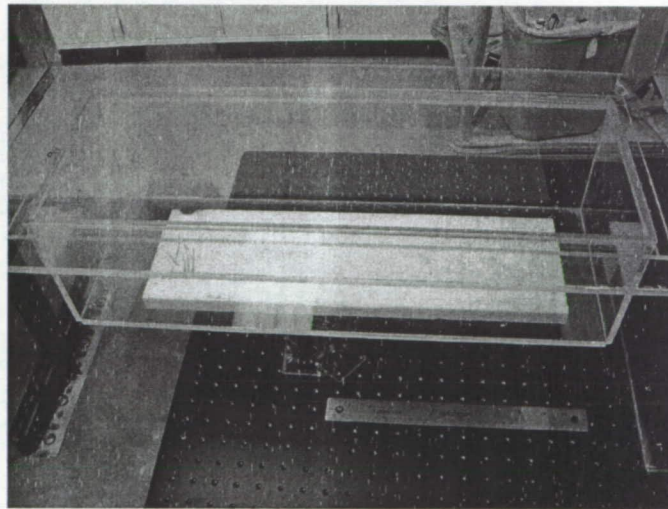
## Appendix

Figure 3



Standard direct drive fan radius of 34 in.

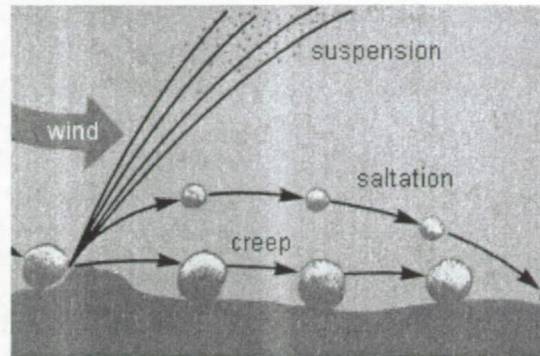
Figure 4



Large sample box shown inserted into test area with one foot ruler

## Appendix

Figure 5



Saltation